RESIDUAL VIBRATION-INDUCED PM NOISE OF A RIGID OPTICAL FIBER SPOOL[1]

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Abstract

Oscillators operating in field applications are subject to much more strenuous environmental effects than those in the laboratory. These environmental effects, such as vibration and temperature fluctuation, have a great impact on the performance of the oscillators; however, many applications require this laboratory-level performance in situ. Opto-electronic oscillators (OEOs) have emerged in recent years as excellent low-noise sources that rival the best radio-frequency (RF) oscillators over broad offset frequencies. An OEO is a delay-line oscillator based on a long optical fiber wound on a spool. The OEO uses an RF-modulated optical signal transmitted down a long fiber-optic cable as a high-Q RF frequency discriminator. OEOs hold promise for many field applications requiring very low noise levels to maintain a high level of precise timing. The phase modulated (PM) noise of these OEOs at offset frequencies below 1 kHz is dominated by environmental effects such as temperature and vibration. This paper studies the impact of external environmental vibration on the optical fiber wound on a spool. Mechanical distortions in the fiber induce time-delay (phase) fluctuations. The spool onto which the fiber is wound is primarily responsible for imparting these vibration-induced delay fluctuations to the fiber and, thus, diminishing the performance of the OEO. In this paper, we compare the vibration-induced phase fluctuations of a 3- km optical fiber wound on spools made of four materials—plastic, foam-covered plastic, ceramic, and foam-covered ceramic. We investigate fiber-on-spool winding and mounting techniques that reduce vibration susceptibility. We present residual PM measurements that compare the vibration sensitivity of an optical fiber wound on these different materials. From this, we give an estimate of the vibration sensitivity of the bare-fiber and associated optical-fiber connectors that may constitute an RF photonic link, serving primarily as a long-distance, low-loss carrier of RF signals, replacing high-loss coaxial cables, for example.

I. INTRODUCTION

Instruments requiring high-performance oscillators are frequently called on to perform reliably in the field; however, field environments are far more strenuous than a laboratory setting. While an oscillator can often provide sufficiently low intrinsic phase-modulated (PM) noise to satisfy particular system requirements in a quiet environment, mechanical vibration and acceleration onboard a vehicle or aircraft can introduce mechanical deformations that deteriorate the oscillator's otherwise low PM

Report Documentation Page	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
01 DEC 2008	**N/A**	**-**

4. TITLE AND SUBTITLE **Residual Vibration-Induced Pm Noise Of A Rigid Optical Fiber Spool**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **National Institute of Standards and Technology 325 Broadway, Boulder, CO 80305, USA**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM002186. Annual Precise Time and Time Interval Systems and Applications Meeting (40th) Held in Reston, Virginia on 1-4 December 2008, The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**UU**	**10**	

noise **[1-4]**. This degrades the performance of the entire electronic system that depends on the oscillator's low PM noise.

An important part of fiber-based communications is the vibration and environmental sensitivity of links. This paper shows some results associated with the frequency fluctuations of a reference oscillator observed through a fiber link that is uniformly vibrated.

Optical fibers are also being used frequently as the frequency-determining element in microwave oscillators for many electronic systems. The opto-electronic oscillator (Figure 1) has emerged in the last few years as an excellent low-noise source rivaling the best electronic radio-frequency (RF) oscillators over broad offset frequencies **[5-7]**. The high spectral purity signal of an OEO is achieved with a long low-loss optical fiber that provides very high Q**.** State-of-the-art RF components, such as modulators and amplifiers, are also used to minimize their noise contribution to the oscillator. However, the close-to-carrier (from a few hertz to 1 kHz) spectral purity of this oscillator is mostly degraded by environmental sensitivities, including the vibration-induced phase fluctuations in its optical fiber **[8]**.

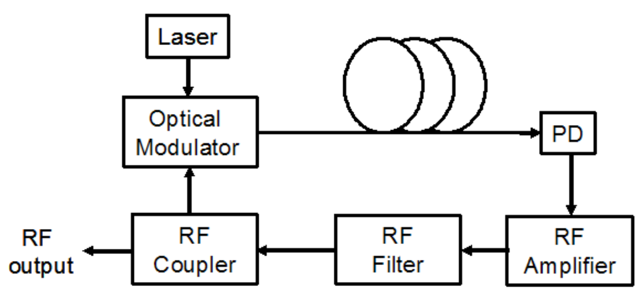

Figure 1. Block diagram of OEO.

The optical-fiber delay line is typically wound onto a spool to contain its length. Since the fiber touches the spool directly, it is the primary means of imparting mechanical vibration to an OEO fiber, directly causing delay fluctuations that diminish the performance of the OEO. Typical materials for fiber spools are plastic and metal, but these can be particularly sensitive to environmental effects. A stiff spool material such as ceramic might not be as sensitive to mechanical vibrations and, thus, might reduce the phase noise vibration sensitivity in an OEO. In addition, a thin layer of foam wrapped around the spool mandrel before the fiber is wound might serve as a "shock absorber" for the fiber, minimizing the vibration and temperature effects of the spool. In this paper, we will compare the vibration sensitivity of fiber wound on four test spools constructed of the following materials: plastic, plastic with foam, ceramic, and ceramic with foam. A comparison of a metal spool to plastic and ceramic may be found in **[9]**. Section II describes the specific materials and spool construction, and Section III addresses the fiber and the method of winding onto the spool. The experimental setup for the PM noise measurements is described in Section IV, and the results are presented in Section V.

II. SPOOL CONSTRUCTION

In order to specifically address the properties of the spool materials, we created spools out of different materials that were as close to the same size and shape as possible, eliminating any effects due to different geometry. The basic spool construction consists of a hollow cylinder fabricated from the test material and capped on both ends with polyoxymethylene (Delrin®) end caps specifically machined to fit each cylinder. Ceramic cylinders were fabricated by cutting high-temperature alumina furnace tubes to length, and we were able to choose a plastic material with the same dimensions. Acrylonitrile butadiene styrene, or ABS, is a plastic commonly used in manufacturing; one of its attractive features is its heat resistance. It is readily available in cylindrical piping with our desired diameter and can be cut to the desired length. Each cylindrical piece is approximately 11.5 cm in diameter with a length between end caps of 10 cm.

Typically, bare optical fiber purchased from a supplier comes on a generic plastic spool that has a layer of thin foam wrapped around it onto which the fiber is directly wound. In addition to our initial two materials, we also created two additional spools to compare the effect of a foam layer. Foam taken from empty supplier spools was applied to a second ABS plastic spool and a second ceramic spool for a preliminary comparison of the effects of this extra layer on vibration-induced PM noise.

III. OPTICAL FIBER AND WINDING

Each spool was wound with 3,000 m of single-mode optical fiber (Corning's SMF-28). As well as ensuring that the size and shape of all of the spools were nearly identical, it was also important for the fiber to be wound the same on all the spools to eliminate any effects due to differences in tension and fiber layering. To ensure our windings were as uniform as possible, a fiber winder was built in our lab for this application.

Precision fiber winding has been studied in great detail **[10]**. Many methods have been proposed for winding techniques that minimize losses in the fiber due to winding; however, at this initial stage in our investigation, we are concerned only with the relative effects of the spool material. This requires consistency between all our spools, but not that they be meticulously wound in this case. Our main concerns were winding tension and fiber placement.

Figure 2 shows the current version of our fiber winder, indicating the mechanisms used to control the braking and tensioning. Tension on the fiber is generated by the motor-turned take-up spool pulling the fiber from the factory-wound feed spool on the other end. A friction brake on the shaft of the feed spool allows free rotation, but prevents rocking due to a sudden decrease in tension. Two fixed rollers and one roller on a pivoting arm also adjust to provide a relatively constant tension on the fiber. A computer-controlled lead screw precisely places a Teflon feed eyelet through which the fiber is threaded, and each consecutive turn of the fiber is wrapped precisely onto the take-up spool as it rotates. With these tension and placement controls, we can create very similar windings among all of our test spools.

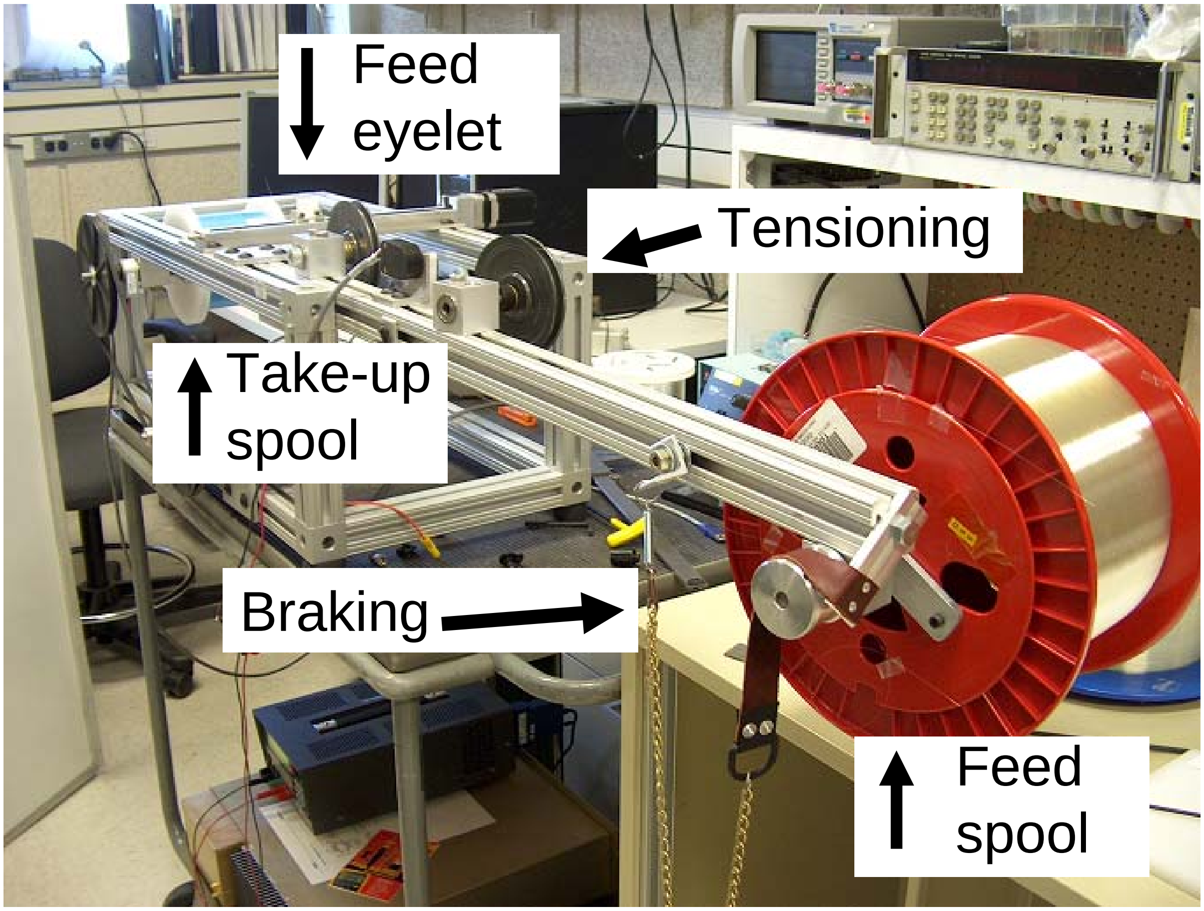

Figure 2. Newest version of in-house fiber winder.

IV. EXPERIMENT

Figure 3a shows the residual PM noise measurement system used to measure the PM noise of the test fibers. The output of a 1550-nm communications-grade laser is sent into an optical modulator, then amplitude modulated by a 10 GHz RF synthesizer signal. This modulated optical signal is split between two channels, each consisting of a 3,000 m SMF-28 fiber wound on a cylindrical spool, a photodetector (PD), and an RF amplifier. A phase shifter in one channel maintains quadrature between the two arms, and a mixer combines the signals, canceling out the common-mode PM noise. The output voltage noise of the mixer, which is proportional to residual PM noise of the PD, amplifiers, mixer, and fiber (the dominant source of noise under vibration), is then measured on a fast Fourier transform (FFT) analyzer.

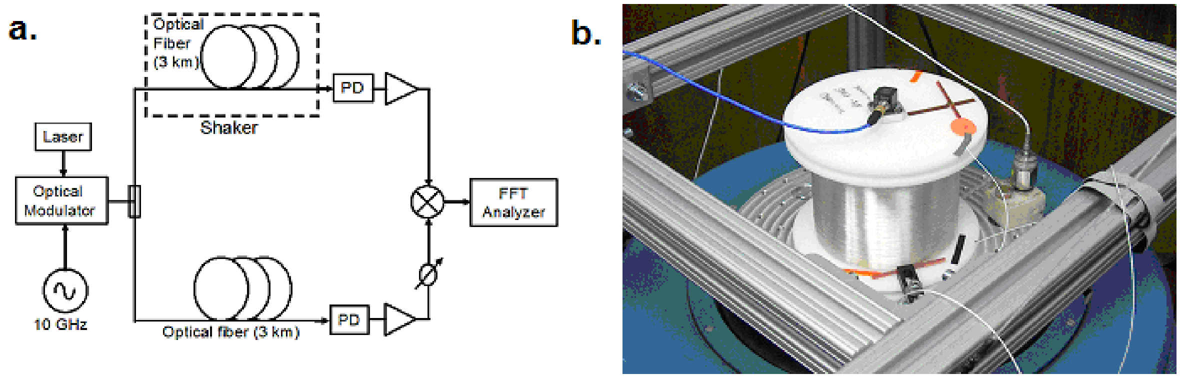

Figure 3. (a) Residual PM noise measurement system. (b) Test spool mounted to the vibration table.

One branch of the measurement system includes one of the 3-km test spools. The spool is mounted to a vibration table that is driven by a computer-controlled waveform generator and high-power amplifier. The output signal driving the table is controlled by the feedback of an accelerometer mounted to the table surface next to the fiber spool. For these tests, the spool is vibrated with a constant-acceleration (*g*) power spectral density of 1 mg^2/Hz (rms) between 10 Hz and 2 kHz. This test reflects typical random vibration that equipment would experience on board a vehicle or aircraft. The second branch of the measurement system includes a delay equalizing spool of the same length that remains stationary during the test.

All five test spools are mounted in the same manner for each measurement. Each spool is mounted with the cylinder's axial direction (axis z) normal to the plane of the vibration table (Figure3b). The x and y axes are parallel to the plane of the vibration table; due to the rotational symmetry of the cylinder, these axes are equivalent and may be represented as one single radial axis. However, the scope of this paper will focus only on the z axis, since it has been shown that vibration sensitivity is greatest along this axis **[11,12]**.

Once the spool is mounted onto the vibration table, a measurement is first taken to observe its noise level while stationary. Then the vibration table is turned on and shaken according to the parameters described above. The residual, vibration-induced PM noise level of the spool is then measured.

V. RESULTS

Figure 4 shows the results of the vibration tests for the four test spools. At rest with no vibration, all the spools have roughly the same noise level, indicated by the black plot. Under vibration, a raised plateau in the noise forms within the range of random vibration (10 Hz to 2 kHz). The noise performance of the plastic spool degrades the most compared to the other spools. While better than plastic, the ceramic spool also experiences a large increase in noise level within the vibration frequency range. However, the two foam-wrapped spools show superior performance to that of their respective foamless spools. The noise level of the plastic with foam spool is around 15 dB lower than that of the plastic spool, and the ceramic-with-foam spool shows up to 20 dB lower vibration-induced noise in some places than the basic ceramic spool.

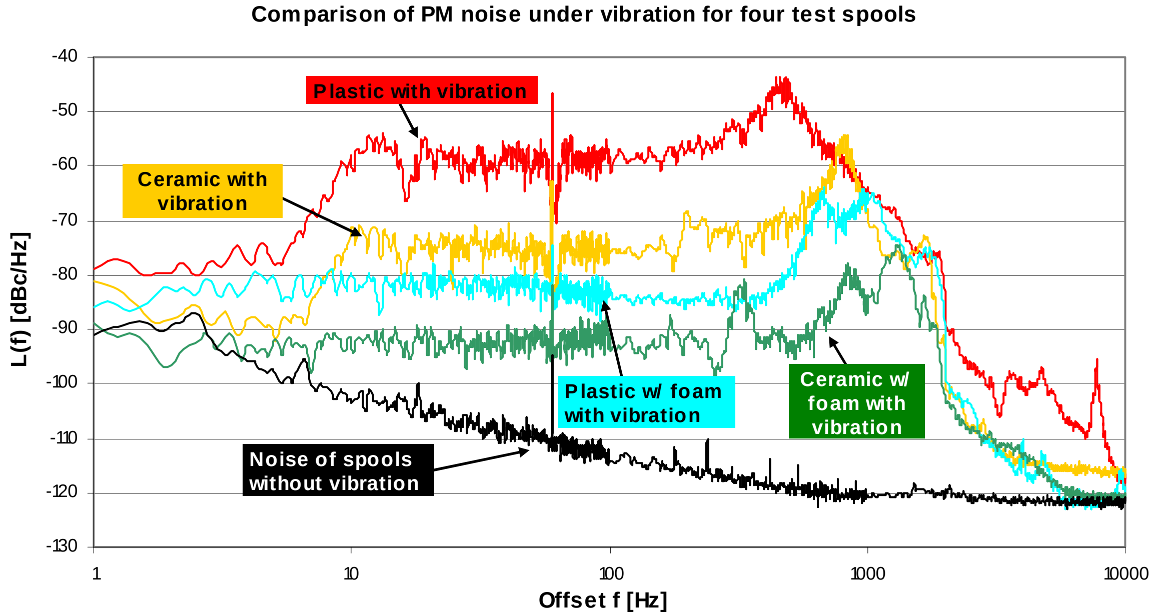

Figure 4. Single-sideband PM noise (L (f)) results for the four test spools.

Figure 4 can be represented as the spectra of a residual frequency fluctuations $S_y(f)$ rather than L(f). For an oscillator, its frequency is the total rate of change of its signal phase:

$$2\pi\nu(t) = \dot{\phi}(t)\,, \tag{1}$$

where $\nu(t)$ is the oscillator frequency and $\dot{\phi}(t)$ is the time rate of change of the phase. We can then define the fractional frequency fluctuation $y(t)$ as

$$\frac{\Delta\nu}{\nu_0} = \frac{\dot{\phi}(t)}{2\pi\nu_0} = y(t), \tag{2}$$

where $\Delta\nu$ is the change in frequency and ν_0 is the nominal frequency of the oscillator **[13]**. As the vibrating fiber imparts a phase fluctuation to the output of a non-vibrating oscillator (Figure 4), the sensitivity of the corresponding frequency fluctuation can be expressed as gamma (Γ), defined as

$$\Gamma = \frac{2f\cdot 10^{\frac{L(f)}{20}}}{\nu_0\left|A\right|}, \tag{3}$$

where f is the frequency offset from the carrier and $\left|A\right| = \sqrt{2\cdot g}$. This scenario would be one in which the fiber in a data communications link were uniformly vibrated (Figure 5). This Γ is shown in Figure 6 and should not be confused with Γ of the fiber in an OEO (Figure 1). The Γ of oscillators is well-described in **[1,2]** and will depend on other noise contributions in the OEO's feedback-loop components.

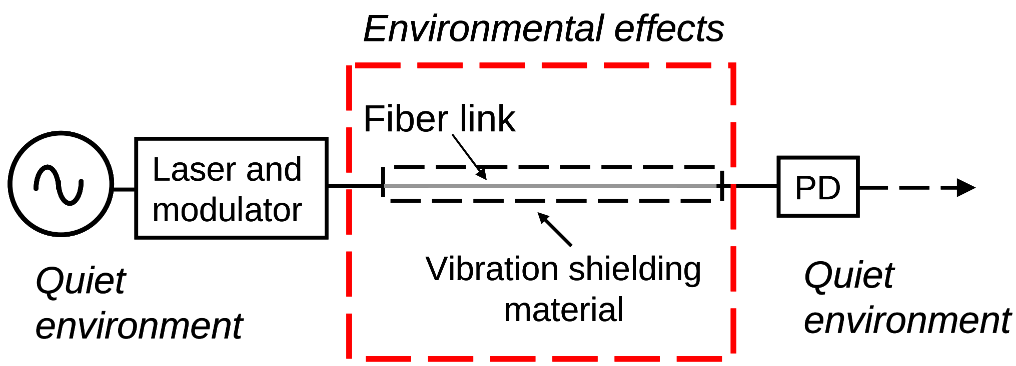

Figure 5. Vibration and environmental effects on the fiber in a data communications link.

Lower values of Γ imply less sensitivity of an oscillator frequency to vibration. Figure 6 shows Γ for all of the test spools. We see that plastic and ceramic have a higher Γ than the two foam wrapped spools, indicating that the foam helps to decrease the vibration sensitivity of the original spool material.

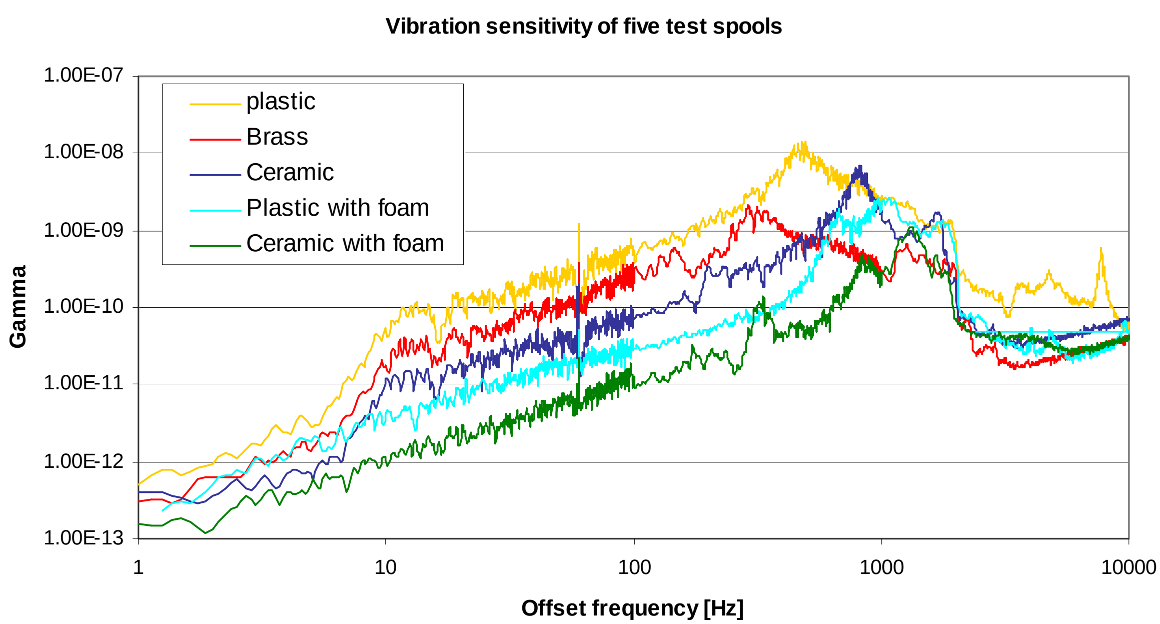

Figure 6. Frequency vibration sensitivity Γ for the test spools.

VI. CONCLUSION

Spool material evidently does have a significant effect on the noise performance of a fiber wound upon a spool. The stresses of vibration on the spool material are imparted to the fiber, degrading its

noise performance. The plastic spool is most affected by the vibration; ceramic alone improves on plastic, but a foam layer between the spool and the fiber evidently absorbs some of the physical changes of the ceramic and plastic spools, causing less stress on the fiber and reducing the vibration sensitivity and the noise level under vibration.

In the future, we would like to explore vibration effects on spools of different shapes and dimensions to see whether changing the geometry improves the noise of the fiber under vibration. The effect of fiber tension will also be explored. There may also be methods of using a free-standing fiber coil without a spool. Ultimately, we hope to discover how best to handle an optical fiber in an electronic system to fully unlock its potential as a low noise system in real-world field environments.

ACKNOWLEDGMENT

The authors would like to thank Kyle Byrnes for his technical contributions to this project.

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